

GREENHOUSE EFFECT OF TRACE GASES, 1970-1980

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Abstract. Increased abundances were measured for several trace atmospheric gases in the decade 1970-1980. The equilibrium greenhouse warming for the measured increments of CH_4 , chlorofluorocarbons and N_2O is between 50% and 100% of the equilibrium warming for the measured increase of atmospheric CO_2 during the same 10 years. The combined warming of CO_2 and trace gases should exceed natural global temperature variability in the 1980's and cause the global mean temperature to rise above the maximum of the late 1930's.

Introduction

CO_2 absorbs in the 7-14 μm atmospheric window which transmits thermal radiation emitted by the earth's surface and lower atmosphere. Increased atmospheric CO_2 tends to close this window and cause outgoing radiation to emerge from higher, colder levels, thus warming the surface and lower atmosphere by the so-called greenhouse mechanism. The CO_2 greenhouse effect has been studied in a series of papers by Manabe (cf. Manabe and Stouffer, 1980) and many other investigators (NAS, 1979). Ramanathan (1975) pointed out that the chlorofluorocarbons (CFCs) also may cause a significant greenhouse effect. Wang et al. (1976) argued that a broad range of trace gases which absorb in the infrared, particularly N_2O , CH_4 and CFCs, may increase as a result of anthropogenic activities, and that their combined warming could be comparable to that caused by CO_2 .

Recent measurements confirm that these trace gases are increasing in abundance. We use these measurements and a 1-D radiative-convective climate model to estimate the global greenhouse warmings caused by N_2O , CH_4 and CFCs in the decade 1970-1980 and compare their effect to the CO_2 greenhouse warming in the same period. We include analytic approximations to the results to allow easy modification for improved trace gas measurements. Finally, we compare the computed trace gas warming in the 1970's to observed global temperature change in that decade and to natural variability of temperature on the decadal time scale.

Observed Trace Gas Abundances

CO_2 has been accurately monitored since 1957 (Keeling et al., 1976). Tabular data through 1980 is available for several stations in the GMCC reports (Herbert, 1980) and from the National Climate Data Center. The global mean increase of CO_2 in the 1970's was 12 ± 1 ppm (parts per million).

CFCs have been monitored since the mid-1970's, as tabulated in the GMCC reports. At the beginning of 1980 there were about 180 ppt (parts per trillion) of CCl_3F at Mauna Loa. The CCl_3F abundance was 80 ppt at the end of 1973. Since almost half of the cumulative CCl_3F release to that time was released in 1970-1973 (CMA, 1980), we estimate the CCl_3F abundance at the beginning of 1970 as 45 ppt, and thus the increase in the 1970's as 135 ppt. CCl_2F_2 abundance was ~315 ppt at the beginning of 1980 and ~250 ppt at the beginning of 1977. Just over half of the cumulative prior CCl_2F_2 release was in 1970-1977 (CMA, 1980), so we estimate the CCl_2F_2 abundance at the beginning of 1970 as 125 ppt and the 1970's increase as 190 ppt. Observations at several sites (Herbert, 1980) and unpublished 3-D model experiments which we have made indicate that the difference between the Mauna Loa and global mean values was positive in both 1980 and 1970 with value of the order of 10 ppt. Error in our estimated 1970-1980 CFC increases is not likely to exceed 20% of the estimated increases.

Comparison of CH_4 measurements in 1965-1980 by several different investigators suggests an increase of 1-3%/yr (Rasmussen and Khalil, 1981a,b). Heidt and Ehhalt (1980) showed that some of the reported measurements early in this period were probably systematically too low by 20%, which could account for a large part of the apparent increase. Rasmussen and Khalil (1981a,b) argue that the total available data suggest that CH_4 is increasing about 1.7%/yr. Recent gas chromatograph measurements of Rasmussen and Khalil (1981a,b) indicate an increase of $2 \pm 0.5\%$ /yr during 1979 and 1980. Graedel and McRae (1980) measured an increase of 0.1 ppm for 1968-1977, ~0.6%/yr. We examine the effect of a 1970-1980 increase from 1.5 to 1.65 ppm, i.e., ~0.9%/year, as an intermediate estimate. Weiss (1981) measured an increase of 0.2%/yr in N_2O abundance for 1976-1980. This growth rate is consistent with the long-term increase inferred from measurements of stored samples (Weiss, 1981). It is also consistent with the measurement by Rasmussen et al. (1981) of $0.3 \pm 0.2\%$ /yr growth for the period 1975-1980. We thus estimate the 1970 N_2O abundance as 295 ppb (Weiss, 1981; Weiss et al., 1981) and the decadal growth as 6 ppm.

We conclude that recent observations confirm that our planet's atmospheric composition is far from being immutable. We recognize that more precise future measurements may substantially modify the estimated changes of specific trace gases. Therefore, we give analytic expressions for the computed greenhouse warmings, so the results can be adjusted in accord with more accurate data.

1-D Radiative-Convective Model

The 1-D RC model uses a time-marching procedure to compute the vertical atmospheric temperature profile from the net radiative and convective energy fluxes. The radiative flux is obtained by integrating the radiative transfer equation over

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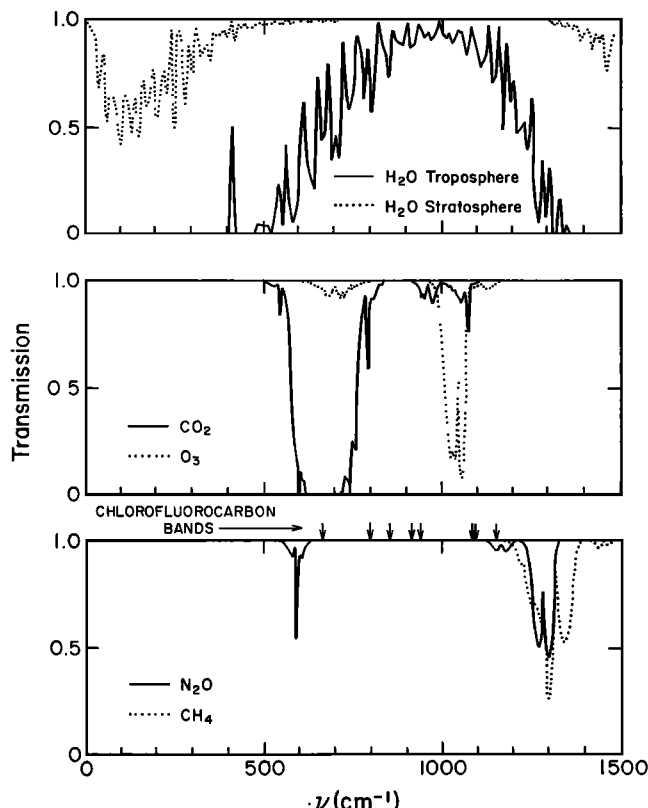


Fig. 1. Transmission of thermal radiation by atmospheric gases for present day abundances. Arrows indicate the locations of CFC bands.

all frequencies, using the temperature profile of the previous time step and an assumed atmospheric composition. The convective flux is the energy transport needed to prevent the temperature gradient from exceeding a preassigned limit ($6.5^{\circ}\text{C}/\text{km}$), which parameterizes effects of vertical mixing and large scale dynamics.

The radiative calculations are made with a method (Lacis et al., 1979) which groups absorption coefficients by strength for efficiency. Pressure and temperature dependent absorption coefficients are from line-by-line calculations for H_2O , CO_2 , O_3 , N_2O and CH_4 (McClatchey et al., 1973) including continuum H_2O absorption (Roberts et al., 1976). Transmission of thermal radiation by these gases is shown in Fig. 1. Climatological cloud cover (50%) and aerosol properties (Toon and Pollack, 1976) are used, with appropriate fractions of low (0.3), middle (0.1) and high (0.1) clouds. Wavelength dependence of cloud and aerosol properties is obtained from Mie scattering theory. Multiple scattering and overlap of gas absorption bands are included.

Model approximations and uncertainties are discussed by Hansen et al. (1981). The model's equilibrium sensitivity is $\sim 3^{\circ}\text{C}$ for doubled CO_2 . The model includes major feedback effects believed to operate in the climate system. The sensitivity for doubled CO_2 is similar to the global mean sensitivity of 3-D climate models (NAS, 1979). It is widely believed that this equilibrium sensitivity is correct to within a factor of two (NAS, 1979).

A detailed description of the radiative calculations will be given in a separate paper, including comparisons with line-by-line and band model calculations.

Equilibrium Warmings

We computed the equilibrium ($t \rightarrow \infty$) warming for arbitrary changes of the relevant trace gases, and fit the results with an analytic expression:

$$\Delta T_{\text{eq}}(^{\circ}\text{C}) = 0.57(\text{CH}_4)^{0.5} + 2.8(\text{N}_2\text{O})^{0.6} - 0.057 \times \text{CH}_4 \times \text{N}_2\text{O} + 0.15 \times \text{CCl}_3\text{F} + 0.18 \times \text{CCl}_2\text{F}_2 + 2.5 \ln[1 + 0.005 \Delta \text{CO}_2 + 10^{-5}(\Delta \text{CO}_2)^2] \quad (1)$$

where the abundances are in ppm except CCl_3F and CCl_2F_2 which are in ppb; the CO_2 amount is in ppm above a reference value of 300 ppm. Equation (1) fits the 1-D model results to better than 5% for abundances $\text{CH}_4 < 5$ ppm, $\text{N}_2\text{O} < 1$ ppm, $\text{CCl}_2\text{F}_2 < 2$ ppb, $\text{CCl}_3\text{F} < 2$ ppb, and $\Delta \text{CO}_2 < 300$ ppm; the third term corrects for overlap of the CH_4 and N_2O bands.

The sensitivity we find for increase of CFCs from 0 to 2 ppb is 0.65°C , significantly smaller than the 0.9°C obtained by Ramanathan (1975). This difference warrants detailed comparison of the models and assumptions employed, though we have carefully checked our calculations and are confident that they are accurate. It is sufficient for now to note that our conclusions would not be qualitatively affected by the existence of a stronger sensitivity to changes in CFC abundance.

The equilibrium warming for the CO_2 , CH_4 , CFCs and N_2O added to the atmosphere in the 1970's follows from (1). As indicated in Table 1 and Fig. 2, the 12 ppm increase of CO_2 yields an equilibrium warming of 0.14°C . The other trace gases known to have increased in abundance, CH_4 , N_2O and the CFCs, each yield a substantially smaller warming, but their net equilibrium warming is 0.10°C , of the same order as the CO_2 warming.

Other trace gases should not alter this comparison. Ozone warrants special attention, because of its strong band at $9.6\mu\text{m}$ (Fig. 1) and the possibility of anthropogenic effects on O_3 abundance. The effect of O_3 on surface temperature depends strongly on the altitude of the abundance change. Tropospheric O_3 is more effective than stratospheric O_3 in influencing T_s because the stratospheric temperature responds more or less locally, while the tropospheric temperature is tied to the surface by convection and dynamics. Heath (private communication) estimates that stratospheric O_3 at 30–50 km decreased $\sim 5\%$ in the 1970's. This would cause an equilibrium decrease of T_s by ~ 0.02 . However, anthropogenic effects could increase tropospheric O_3 (Logan et al., 1978; Hameed, et al., 1980); there is observational evidence for a small increase in column-integrated O_3 amount, but the magnitude does not exceed measurement uncertainty (Heath, private communication). Thus the sign of an O_3 influence on T_s is uncertain, but the magnitude of any effect in the 1970's should have been small. Several other trace gases may have increased in the 1970's as a result of man's activities

Table 1. Greenhouse effects of several trace gases.

Species	Arbitrary change			1970–1980 change		
	a_0 (ppb)	Δa (ppb)	$\Delta T_{\text{eq}}(^{\circ}\text{C})$	a_0 (ppb)	Δa (ppb)	$\Delta T_{\text{eq}}(^{\circ}\text{C})$
CH_4	1600	1600	0.26	1500	150	0.032
N_2O	280	280	0.65	295	6	0.016
CCl_3F	0	2	0.29	0.045	0.135	0.020
CCl_2F_2	0	2	0.36	0.125	0.190	0.034
CO_2	300000	300000	2.9	325000	12000	0.14

(Wang et al., 1976). It seems unlikely that the equilibrium warmings of other gases exceeded a few hundredths of a degree, but that could make the net greenhouse effect of the non-CO₂ gases as great as that for CO₂. Clearly a continuing inventory of atmospheric composition is needed.

Our best estimate of the trace gas equilibrium warming in the 1970's is thus 70% of the CO₂ warming. The major uncertainty is the magnitude of the CH₄ growth, though there is general agreement of an increase in the 1970's. We conclude that the trace gas warming was probably between 50% and 100% of the CO₂ warming in the 1970's.

Expected Surface Warming, 1970-1980

The portion of the equilibrium warming which would be expected to appear by 1980 depends on the effective heat capacity of the ocean. The upper 'mixed' layer (~100 m) of the ocean provides the initial reservoir to be heated by an increased greenhouse effect. If there were no exchange between the mixed layer and deeper ocean, the mixed layer would respond to incremental heating by approaching its new equilibrium temperature, $T_0 + \Delta T_{eq}$, exponentially with e-folding time

$$\tau \sim \Delta T_{eq} Q / f \quad (2)$$

where Q is the mixed layer heat capacity and f the initial net heating of the surface. For the trace gases (including CO₂) added to the atmosphere in 1970-1980 (Table 1), f is 0.3 W m⁻² (compared to ~4 W m⁻² for an instantaneous doubling of CO₂). f is independent of feedbacks and hence τ , like ΔT_{eq} , is proportional to any feedback factors which amplify ΔT_{eq} (Hansen et al., 1981). Thus the relaxation time $\tau \sim 6$ years, obtained from (2) for the above value of ΔT_{eq} and a 70m global mean mixed layer thickness, applies to the model with equilibrium sensitivity ~3°C for doubled CO₂.

The feedbacks make τ large enough that the exchange of heat between the mixed layer and thermocline cannot be neglected, further increasing the time required to reach full equilibrium warming of the surface. The lag in surface temperature response can be estimated with a simple box diffusion model (Oeschger et al., 1975) with instantaneous mixing in the upper 100 m and diffusion into the deeper ocean with diffusion coefficient $k \sim 1$ cm² s⁻¹. This model, which is consistent with other simple models for heat penetration into the ocean (Thompson and Schneider, 1979; NAS, 1979; Hoffert et al., 1980; Cess and Goldenberg, 1981), leads to the conclusion that only about half of the equilibrium warming for the gases added to the atmosphere in the 1970's should have appeared by 1980. The expected greenhouse warming in the 1970's is thus ~0.1°C, plus residual warming from gases added prior to 1970. The latter increment is probably not more than ~0.05°C, since increases in trace gases other than CO₂ were probably small prior to 1970. The net greenhouse warming expected for the 1970's is thus 0.1-0.2°C.

Observed Atmospheric Temperature Trend

Recent analyses agree that the Northern Hemisphere surface air and tropospheric temperatures increased by about 0.1-0.2°C in the 1970's (Jones and Wigley, 1980; Angell and Korschover, 1978 and

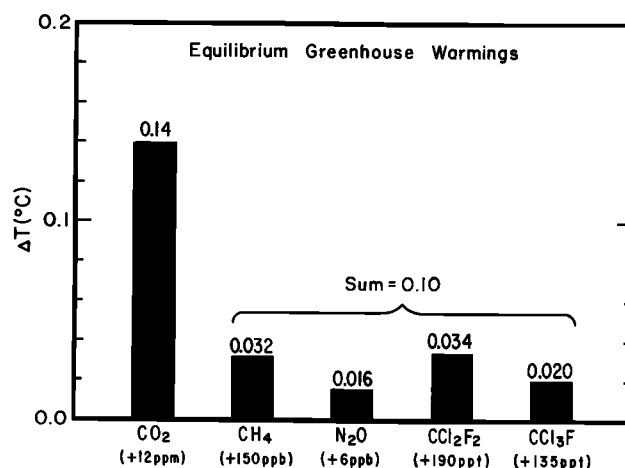


Fig. 2. Equilibrium greenhouse warmings for estimated 1970-1980 abundance increases of several trace gases, based on 1-D RC model with sensitivity ~3°C for doubled CO₂

private communication; Hansen et al., 1981). The latter authors also analyzed the global mean temperature trend, for which they found a similar increase in the 1970's.

Normal fluctuations of the smoothed global mean temperature are of the order of 0.1°C for decadal time scales. For example, the standard deviation, σ , of the 5-year-smoothed global mean temperature of Hansen et al. (1981) is 0.1°C for 10 year intervals. Therefore, although the observed global temperature change in the 1970's is consistent with that expected from increased trace gas abundances, the change is too small to be confidently ascribed to the greenhouse effect.

Global warming due to increased abundance of infrared absorbing gases can be expected to exceed natural variability in the 1980's, when the residual warming due to gases added to the atmosphere in the 1970's should appear in observed temperatures as well as about half the equilibrium warming of gases added in the 1980's. The effect of trace gases, including CO₂, is likely to be a warming 0.2-0.3°C in the 1980's. The total temperature rise in the 1970's and 1980's should thus substantially exceed natural variability for a 20-year period.

Discussion

The computed greenhouse warming for reported increases of several trace gases in the 1970's is about 70% as large as that due to the CO₂ increase in the same decade. Despite uncertainties in the abundance increases, we conclude that these trace gases caused a greenhouse warming in the 1970's comparable to that due to increasing atmospheric CO₂. This reemphasizes the conclusion of Wang et al. (1976) that it is important to establish accurate monitoring of a number of trace atmospheric constituents including CH₄ and N₂O.

There is little evidence that these trace gases added much to the CO₂ greenhouse effect prior to 1970. For example, from their absolute abundance we know that most of the CFCs in the atmosphere were added during the past decade. However, the combined growth of CO₂ and other trace gases in the 1970's was sufficient to cause a net computed

greenhouse warming for the decade similar in magnitude to natural decadal temperature variability, and the combined warmings in the 1970's and 1980's should exceed natural variability. Indeed, unless the greenhouse warming is counteracted by some abnormal cooling effect, e.g., volcanic activity much greater than usual or a decrease of solar irradiance, the global mean temperature should rise well above the level of the 1930's. Several measurements, especially of trace gas abundances and solar irradiance, are needed during the 1980's to permit cause and effect association of observed warming with the greenhouse gases.

These results underline the importance of understanding man's impact on tropospheric composition. It is now clear that several trace gases significantly impact the radiation and energy budget at the earth's surface and are capable of modifying our climatic environment. It is thus imperative to develop a basic understanding of the factors determining the abundance of such trace gases and their sensitivity to anthropogenic influence.

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